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Magneto-Optics of GaAs Quantum Wire Lattices Grown by Selective-Area MOVPE

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Abstract. We report the magneto-optical measurement of GaAs quantum wire lattices of 0.7 micrometer period grown on GaAs(111)B substrates by using the selective-area MOVPE technique. We measure the photoluminescence (PL) spectra at 60 mK from the triangular and the Kagome lattice patterns as well as from the unpatterned single quantum well (SQW) as a reference. While the PL from acceptors is dominant in all the samples, the PL spectra have a different peak between the wire structures and the SQW. When we apply a perpendicular magnetic field to the samples, the PL intensities slightly decrease up to 100 mT and then increase at higher magnetic fields with periodic oscillations in the triangular and the Kagome lattices. This oscillation is possibly attributed to the interference effect of electrons in the lattice patterns threaded by the magnetic flux.

1. Introduction

One of the future goals in nanotechnolgy is to build a desired lattice in usual solids since the lattice structure determines the electronic properties in solids. This type of band engineering is difficult task at present because the lattice structure is strictly determined by the atomic nature of individual elements. One of the possible candidates to realize an artificial lattice is a quantum-dot lattice which is an array of quantum dots (artificial atoms) coupled with each other to form an artificial crystal. In dot-lattices, one can achieve electron correlation effects such as ferromagnetism [1, 2] and superconductivity [3], that have been predicted in mathematical models of lattice systems. It has been shown that a Kagome network of quantum wires effectively acts as a Kagome dot-lattice where electrons are well localized at the cross points of two wires since the effective width of the quantum wires at the cross points is larger than the normal width of the wire. The proposed structure in Ref. 1 consisted of InAs quantum wires surrounded by InGaAs barrier regions. The width of each quantum wire was assumed to be 0.104 μm and the lateral size of each two-dimensional unit cell was 0.72 μm. In this case, the energy separation between up- and down-spin bands is 0.05 meV which is sufficient to experimentally observe ferromagnetic properties at low temperature. Many theoretical studies have been carried out on the semiconductor Kagome lattice structure, but to date there is no experimental realization of it. Such an artificial lattice structure would be particularly interesting because one could

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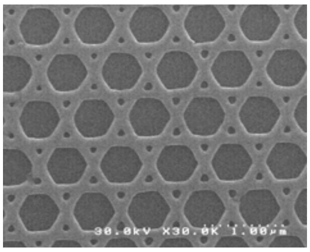

Figure 1. SEM image of Kagome lattice structure grown by the SA-MOVPE method.

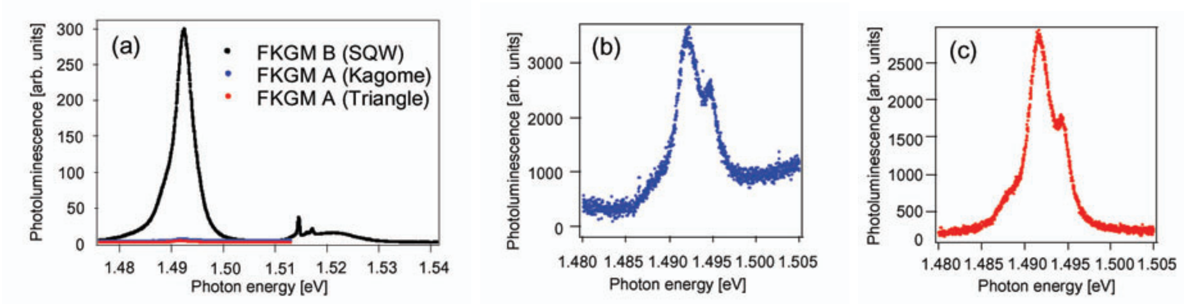

Figure 2. (a) Photoluminescence spectra of the single quantum well, (b) Kagome lattice and (c) triangular lattice.

engineer the energy band structure by the semiconductor fabrication technology. Hence, the present work is aimed at fabricating the semiconductor Kagome lattice structure.

2. Sample Fabrication

Selective area metalorganic vapor phase epitaxy (SA-MOVPE) is utilized to fabricate the wire-lattice structure. Triangular and Kagome lattice patterns were formed with a period of 0.7 micrometer. A low-pressure, horizontal, rf-heated, MOVPE system was used for the selective area growth [4, 5]. GaAs/AlGaAs quantum wells were grown on the masked substrates with the above conditions to form the Kagome lattice structure. The layer structure typically consisted of a 100 nm GaAs buffer layer, a 20 nm bottom AlGaAs barrier layer, a 10 nm GaAs well layer, a 20 nm top AlGaAs barrier layer and a 10 nm GaAs cap layer.

3. Photoluminescence Measurements

We measured the photoluminescence (PL) spectra at 60 mK from the triangular and the Kagome lattice patterns grown on GaAs(111)B substrates as well as from the un-patterned single quantum well (SQW) as a reference. The PL is measured by exciting the samples at 532 nm with 100 mW/cm^2 continuous laser via an optical fiber. The PL from the sample is dispersed through a 100-cm monochromator and detected by a charge-coupled device cooled by liquid nitrogen.

From the PL spectrum $I(E)$, we evaluated the first moment of the transition energy $M = \int I(E)EdE/\int I(E)dE$ and the total photoluminescence intensity $I = \int I(E)dE$. While the acceptor PL is dominant in all the samples as shown in Fig. 2, the PL spectra have a different peak between the wire structures and the SQW. The acceptor PL from the SQW shows a single peak in Fig. 2(a), whereas the PL spectra of the Kagome lattice and the triangular lattice are split into two peaks in Figs. 2(b) and (c). By taking the first moment of these spectra, the

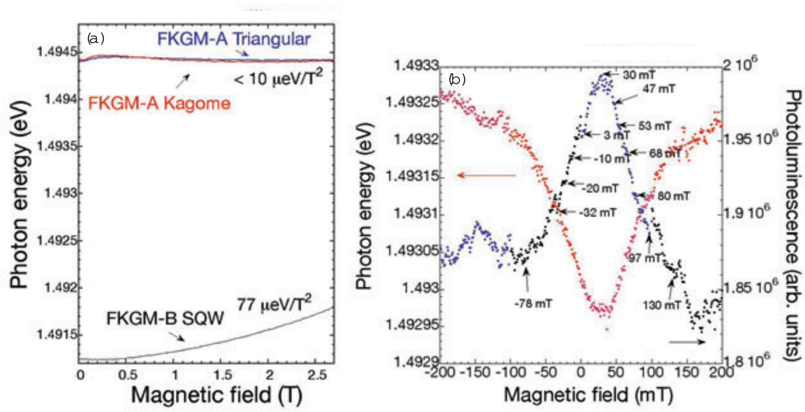

Figure 3. (a) Magnetic field dependence of the transition energy for the single quantum well, the triangular lattice, and the Kagome lattice. (b) The transition energy and the photoluminescence intensity for the Kagome lattice in the weak magnetic field regime.

energies of the Kagome and the triangular lattice are about 3 meV higher than that of the SQW. This can be attributed to an increase in the energy by the lateral confinement of the quantum wire.

As shown in Fig. 3(a), when we apply a perpendicular magnetic field to the samples, a monotonic increase is observed in the peak energy in the SQW due to the diamagnetic shift. The magnitude of this shift is about ΔM=77 μeV/T^2. The diamagnetic shift in bulk is 109 μeV/T^2 and the 2D limit is 20 μeV/T^2. Our data is reasonably in between these values. In the triangular and the Kagome lattices, the diamagnetic shift is suppressed due to the confinement of the lateral structure. The observed shifts for these samples are at most 10 μeV/T^2. In addition, in the triangular and the Kagome lattices, the PL intensities slightly decrease up to 100 mT as shown in Fig. 3(b), and then increase at higher magnetic fields. The peak position of the split peaks which are observed in the lattice structures (see Fig. 2(b) and (c)) is almost unchanged but the peak heights are decreased by applying magnetic fields below 200 mT. This behavior gives rise to the intensity decrease shown in Fig. 3(b) as well as the energy shift when we take the first moment of the spectra shown in Fig. 3(b). At present, there is no clear explanation for this behavior as well as the origin of two split peaks in the wire structures. Even when the measured temperature is increased up to 1 K, this magnetic field dependence is not significantly changed.

In the small magnetic field regime, periodic oscillations are observed with a periodicity of about 10 mT in the total PL intensity in the Kagome lattice as shown in Fig. 3(b). The corresponding magnetic field of the magnetic flux threaded in an equilateral triangle or an equilateral hexagon with sides 350 nm to be one magnetic quanta are B_1 =78 mT and B_2 =13 mT, respectively. The observed oscillation period is close to the magnetic field B_2 for the hexagonal area. Since the holes are trapped by the acceptors and not affected by weak magnetic fields, this oscillation in the PL intensity is induced from the magnetic field dependence of the electron states. Moreover, the oscillation vanishes when the measured temperature is raised from 60 mK to 1 K and the SQW sample does not show such oscillations. Therefore, this oscillation is possibly attributed to the quantum interference effect of electrons in the lattice patterns threaded by the magnetic flux. We can suggest that this oscillation is the Altshuler-Aronov-Spivak (AAS) effect [6] with a periodicity of $B_2/2$. Unfortunately, a lack of reproducibility of the result prevents a further quantitative analysis. We measured 5 samples and not all the samples show this oscillation. The triangular lattice shows faint oscillations but we could not deduce their periodicity. The oscillation disappears even in the same sample after the several cool-downs and warm-ups. Thermal cycle may affect the defects and destroy the quality of the sample. The observation of the AAS effect in our quantum wire lattices indicates that the electron wavefunction is coherently spreading over the unit cell. Although we could not present a direct evidence of electron band-structure, we have at least demonstrated the coherent electron-state which is necessary for a formation of the band structure.

In summary, we reported the photoluminescence measurement of GaAs quantum wire lattices grown by the SA-MOVPE technique. We obtained periodic oscillations in the PL spectra in the triangular and the Kagome lattices which may be attributed to the interference effect of electrons in the lattice patterns threaded by the magnetic flux.

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